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ARMAMENT RESEARCH AND DEVELOPMENT

ESTABLISHMENT

GUNS AND AMMUNITION DIVISION

R.A.R.D.E. MEMORANDUM 34/65

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Measurements of the drag and yaw of '100 grain' flechettes

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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 34/65

Measurements of the drag and yaw of '100 grain' flechettes

K.E.B. Green (B2)

T.O. Andrews (B2)

Summary

Firings in the B2 Aeroballistic Range of various designs of flechettes of l/d = 11.4 and order 100 grain mass have established the yaw-travel relationships for both point-first and backwards-launched rounds. The loss of velocity with travel has been measured and drag coefficients estimated where appropriate.

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1. INTRODUCTION

An experimental study of the aerodynamic drag and yaw characteristics of different designs of flechettes of order 100 grain mass has been carried out with a series of firings through the B2 Aeroballistic Range. The study was part of an assessment of the performance of flechettes against lightly armoured targets, the flechettes being launched from a weapon warhead with possible large variations of initial yaw and velocity.

Establishment of the velocity-travel and yaw-travel relationships would enable the strike velocity and angle of attack of individual flechettes to be estimated after a given travel, following launch at different velocities and attitudes.

Flechettes were fired both point-first and base-first and their subsequent behaviour observed in the range. In the text rounds fired from the gun with their base first initially are referred to as backwards-launched. Their subsequent motion will eventually become either base-first or point-first, these terms being self-explanatory.

2. FLECHETTES

2.1 General

The armour penetrating performance of one type of flechette, the flared base flechette, had already been assessed in firings and the external ballistic firings started using this design. All flechettes were made with the same overall length (2.0 inch) and diameter (0.175 inch) giving an l/d ratio of 11.4. The flechette masses, ranging from 63 to 109 grain, varied with the different tail designs.

The flechettes are intended for close stacking in the warhead and tail design was such that the best stacking could be obtained.

2.2 Flared base flechette

This flechette, shown in figure 1a, is made of mild steel and has a mass of 109 grain. The base flare is intended to stabilise the flechette by its base form drag. Firings of this flechette launched backwards showed that it had no tendency to turn to point-first flight. Some variants, shown in figure 1b, with asymmetric base bevel or hollowed flare were also tried to induce turn over from the backwards-launched condition.

2.3 Finned flechette

This flechette, shown in figure 2, is also made from mild steel bar and has a mass of 79 grain. The fins are of maximum height compatible with close stacking; they can be stacked with their axes parallel, half pointing in each direction, such that each flechette is in contact along its length with four flechettes around it which are pointing in the other direction.

2.4 Hollow base flechette

This design, shown in figure 3, was included in this study to determine whether a long simple cone-cylinder flechette could be stabilised sufficiently by moving the centre of mass closer to the nose, this being done by drilling a hole into the base. Its mass was 63 grain. If this flechette proved satisfactory, then a simple pointed hexagonal section flechette with a hollowed base could be considered; this would, of course, have the optimum stacking property.

3. EXPERIMENTAL DETAILS

3.1 Gun and ammunition

A 20 mm Hispano barrel bored out to 0.830 inch smooth bore, was used for all the firings.

Charges of 150 to 500 grain of NRN propellant gave muzzle velocities in the velocity range 2000 to 5000 ft/sec.

3.2 Sabots and base-plugs

The flechettes were fired, centred in perspex sabots, with nylon base-plugs to act as gas seal and pusher.

The perspex sabots, shown in figure 4, were split along the thin web into four pieces and were re-assembled around the flechette before loading into the muzzle end of the gun. Earlier firings in the open range of these sabots, used without this prior splitting, had resulted in many wild rounds; the aerodynamic forces had not been sufficiently large to ensure early and proper separation of sabot pieces from the flechette.

The base-plugs, also shown in figure 4, were basically the same for all types of round, with one exception mentioned later, with suitable variations in the forward surface to suit the flechette and type of launch.

For all backwards-launched flechettes this front surface had a small 60° cone to take the flechette nose. Additional driving force to the backwards-lunched flared base flechette was given by the perspex sabot pushing onto the coned surface of the flared base.

For forwards launching, a small steel disc let into the front surface of the base-plug prevented the finned and hollow base flechette from"setting back" into the nylon.

Two hollow base flechettes were fired point-first using special base-plugs; these were 1 inch long with a forward pointing central steel pin which engaged in the forward end of the hole in the flechette. However, no results were obtained with these as the flechettes were well off line. A third hollow base flechette, launched in the usual perspex sabot and pushed by the normal, 'steel disced' base-plug, did give some results but again was somewhat off line.

3.3 B2 Aeroballistic Range

The flechettes were fired through the free-flight Aeroballistic range, at B2 Woolwich. This is a 450 ft long brick tunnel which houses up to 20 spark-camera stations and a space reference system consisting of three steel wires stretched along 400 ft of the range; this is the instrumented portion. The range coordinate axes are taken as OX, along the range, OY, the horizontal to the right and OZ, the vertical downwards.

Each spark-station records a pair of orthogonal indirect shadowgraphs of the reference system and the moving projectile. From the shadowgraphs, the projectile position and attitude can be deduced. The time of occurrence of each spark event is also recorded. Hence both the yaw-travel and travel-time histories are recorded for each round fired.

For these firings a reduced length (130 ft) of the range was used because of the large projectile dispersion. Ten spark-camera units were used in the early firings; these were increased to fifteen later when the units were then at 30, 35, 42.5, 47.5 ft and at 10 ft intervals up to 117.5 ft from gun muzzle.

For the later rounds some direct shadowgraphs were taken at 14.5 ft and 19.5 ft from the muzzle. Complete measurements of projectile position were not obtainable from these as the reference wire system did not feature in them.

The range is more fully described in an RARDE Memorandum in preparation (Ref. 1).

4. ANALYSIS OF RESULTS

4.1 Yaw-travel

Measurements of the spark photographs and subsequent analysis give the projectile position and attitude at the known instant of spark time at each spark station. For this report the yaw is taken as the angle between the projectile axis and the OX axis along the range. The angle between the trajectory tangent and the OX axis has been ignored; this was never greater than 1° and is small compared with the yaw angles measured.

For each round the apparent yaw both in the horizontal and vertical planes was plotted against travel and a pair of smooth curves drawn through these points. Additionally on a polar diagram, yaw as amplitude was plotted against orientation as argument. From these curves a true yaw-travel curve has been deduced for each round. The polar diagrams show the yaw to be largely planar.

4.2 Velocity-travel

The velocity-travel has been calculated for each round fired from the space-time data. The velocity of the point-first rounds varied nearly linearly with travel over the recorded distance. The velocity of the backwards-launched r rounds falls rapidly in early travel whilst the flechette is tumbling into point-first flight after which velocity falls off more slowly. This can be seen in figure 10 by comparing Rd 64 (point first) with the remaining, backwards-launched, rounds.

For the point-first rounds, the basic law of drag proportional to square of velocity was taken, i.e.:-

$$\frac{d^2s}{dt^2} = -aV^2 \qquad \text{Equation 1}$$

For each round the drag constant 'a' of equation 1 was calculated by a least squares fit of the straight line (derived from equation 1)

$$\log_e V = \log_e V_o - as \qquad \text{Equation 2}$$

to the values of V and s (velocity and travel) deduced from the space-time data.

From equation 2, using the calculated value of 'a', the muzzle velocity was evaluated by extrapolating travel back to the muzzle.

The Drag Coefficient, C_D, was also calculated for each of the point-first and the base-first rounds in the following manner:-

$$\text{Drag force} = \tfrac{1}{2} C_D \rho A V^2 \qquad \text{Equation 3}$$

$$\text{Retardation} = \text{drag force}/m = aV^2 \qquad \text{Equation 4}$$

$$\text{hence from 3 and 4} \quad C_D = \frac{2ma}{\rho A} \qquad \text{Equation 5}$$

where
- m = projectile mass — lb
- a = fitted constant — ft^{-1}
- ρ = air density — 0.07631 lb ft^{-3}
- A = effective projectile area — ft^2
- V = mean velocity — ft s^{-1}

In the calculation of C_D a mean value of A was used; this was estimated from the yaw-travel curve and the geometrical relationship between yaw and projected area of flechette.

5. FINNED FLECHETTES

5.1 Yaw, point-first

The curves of yaw-travel for the point-first rounds are not reproduced but show that the yaw is well below 10° and varies with travel in an apparently random manner. From these curves the mean yaw over the recorded travel was estimated for each round and is given in Table 1, column 7.

The variation in projectile area with flechette yaw has been calculated from the flechette geometry for yaw angles up to 30°. Two cases were considered 1, the yaw in a plane containing a pair of opposite fins and 2, the yaw in a plane bisecting a pair of adjacent fins. The area in the latter case was higher by up to about 7½% and the mean of the two was taken in determining the average projected area for each round.

The mean area for each round was obtained from a curve of projected area against travel. The mean area is also given in Table 1 for each round.

The higher velocity rounds gave the largest yaw values - Rds 56, 58 and 59 having a mean yaw of 4.7^{o}, 7.5^{o} and 5.0^{o} respectively. The yaw is largest for all rounds in the early travel, indicating that some sort of perturbation associated with the intermediate zone or on sabot separation has caused the initial yaw. The yaw gradually damps down and the corresponding mean yaw over travel 90 to 140 ft from the muzzle for the three rounds above are 3.5^{o}, 4.0^{o} and 3.0^{o} respectively. It follows that the flechette is adequately stabilised to keep it in low yaw flight.

5.2 Retardation, point-first

The results from each of the finned flechette point-first rounds are summarised in Table 1. The drag constant, 'a', and drag coefficient, C_D, quoted in the table were deduced from the space-time data as described in Section 4.2. $\bar{V}$ in column 10, is the mean velocity at the mean travel, s, over the recorded length of the trajectory, and it is the velocity appropriate to the value of C_D quoted in the preceeding column. Also given is the 'retardation' expressed in units of ft/sec per ft travel.

Figure 5 gives the values of C_D for the point-first finned and flared base flechettes plotted against $\bar{V}$, expressed here as Mach number. To compare the drag of the flechettes here reported on with other flechettes, figure 5 also includes two curves of C_D versus Mach No. for four finned flechettes (10.2 grain) extracted from a B.R.L. Report (Ref. 2). The upper curve refers to turbulent and the lower to laminar flow over the flechette body. In the velocity range considered, the Reynolds number varies from 1.0×10^{6} to 3.3×10^{6} for both the U.S. 10 grain and the U.K. 80 grain flechettes. The B.R.L. Report quotes that for these Reynolds numbers the flow about the body can be either laminar or turbulent with possible transition either way.

$$\text{Reynolds Number, } R_e = \frac{\rho V l}{\mu}$$

where μ/ρ = kinematic viscosity ($0.1567_{-1} \times 10^{-3}$ $ft^2 s^{-1}$ at N.T.P.)
V = projectile velocity ft s^{-1}
l = body length neglecting fins ft.

It is likely that the high values of C_D and their large scatter in the present firings are due to flechette manufacture; a smooth surface finish had not been **explicitly** specified and chamfering of the leading edges of the fins had been done with a file with some variation between projectiles. However, variations of this type could be expected with, and hence these results may be regarded as typical of, mass produced types.

The velocity-travel for each point-first round over the recorded distance is adequately represented by the fitted equation 2, i.e.

$$\log_e V = \log_e V_o - as.$$

This may be rewritten as $V = V_o e^{-as}$ Equation 6

A main requirement of this study is to determine an expression to enable the velocity to be predicted after any known travel with a given initial velocity. With a suitable value for the drag constant 'a', equation 6 could be used for this. The simplest approach would be to take a constant value of 'a' for all velocities.

However from Table 1 and figure 5 it is evident that there is a tendency for 'a' to decrease as velocity increases. This would have been expected from the C_D - Mach No. curve, figure 5.

The observed V-s data had been obtained over distances of 110 to 130 ft travel. No serious errors are introduced if the curves fitted to the data are extrapolated to cover a distance of 150 ft. Consequently from the fitted Equation 2 of each round, the velocities at 75 ft before and 75 ft after the mid-point travel for the round were calculated. These are given in Table 1; the former as V_0 in ft/sec and the latter, V_{150}, as a fraction of V_0. The value of 'a' quoted for each round is hence appropriate to the velocity midway between these two and is also adequate for the whole range V_0 to V_{150}.

Figure 6 shows drag constant 'a' plotted against V_0. The straight line shown on figure 6 is the regression line of 'a' upon V_0, calculated to be:-

$$a = 0.929 \times 10^{-3} - 0.06316 \times 10^{-6} V_0$$

with a standard error of 'a' of 0.069×10^{-3}, giving confidence limits of $\pm 0.156 \times 10^{-3}$ at a 95% probability.

Thus the velocity of a point-first finned flechette over a travel of 150 ft can be adequately expressed by:-

$$V = V_0 \exp \left\{ 0.929 \times 10^{-3} - 0.06316 \times 10^{-6} V_0 \pm 0.156 \times 10^{-3} \right\} s. \quad \text{Equation 7}$$

for velocities between 2000 and 5000 ft/s.

A stepwise calculation at 150 ft intervals is recommended for estimation of velocities at distances in excess of 150 ft rather than extrapolation of equation 7. For example, between 150 ft and 300 ft equation 7 should be used with V_{150} taken as the new V_0.

The use of equation 7 for velocities above 5000 ft/s and below 2000 ft/s should be undertaken with caution, especially in the latter case where C_D and 'a' will vary more rapidly with velocity.

5.3 Yaw, backwards-launched

Some of the yaw-travel curves for the backwards-launched rounds are reproduced in figure 7. The general shape of these curves were obtained as described in Section 4.1. For these rounds the initial yaw was of course 180°. For round 70 alone of these rounds, an extra station was set up at 14.5 ft travel, of the direct shadowgraph type. The yaw at this travel was 120°; that is still base-first with the projectile axis at 60° to the trajectory. This observation together with the near zero yaw at 30 ft suggested the manner in which this flechette was turning over in the early stages of travel. It was assumed that the other rounds behaved in a similar manner.

From the curves of figure 7, it is evident that, when these flechettes are launched backwards, they turn to point-first flight within about 70 ft of travel and that by 150 ft travel the yaw has substantially died away. In Table 2 the mean recorded yaw for each round in the travel range 100 to 140 ft is given in column 6. This emphasises that the flechette is adequately stabilised as already deduced in Section 5.1.

5.4 Retardation, backwards-launched

The fall of velocity with travel for each of the backwards-launched rounds is given in figure 8. As the velocity is changing so rapidly it would be invalid to try to fit the simple drag law, equation 2, to the observations.

It is also difficult to determine by extrapolation the muzzle velocity for each round from its velocity-travel curve. However, many rounds have been fired through this barrel and the charge weight - muzzle velocity relationship has been reasonably well established. All projectiles fired have been basically similar with similar gas sealing base-plugs which give little bore friction. Muzzle velocities for each charge weight, allowing for the differences on projectile mass, have been estimated and are given in Table 2. Each curve of figure 8 has been extrapolated to the appropriate muzzle velocity. It is evident that this estimate of muzzle velocity is not very accurate.

The velocities at 100 ft and 150 ft have been taken from the velocity-travel curves and the latter are given in Table 2, together with the fractional velocities V_{100}/V_0 and V_{150}/V_0 where

	V_0	= estimated muzzle velocity	ft/sec
	V_{100}	= velocity at 100 ft	ft/sec
and	V_{150}	= velocity at 150 ft	ft/sec

N.B. V_0 here is the estimated muzzle velocity and in Section 5.2 V_0 was at an arbitrary travel taken at 75 ft before mean travel for the convenience of developing equation 7.

It is not possible to see any dependence of V_{150}/V_0 on V_σ as was the case with the point-first rounds; any such trend would be masked by the large round-to-round variations in V_{150}/V_0 due to the rather inexact assessment of V_0.

The mean fractional velocity for all backwards-launched rounds is 0.503 (σ = 0.029) at 100 ft and 0.473 (σ = 0.034) at 150 ft.

The velocity at any distance beyond 150 ft from launch for backwards-launched flechettes can be obtained by taking the fractional velocity at 150 ft as 0.473 to obtain V_{150} and then by applying equation 7 stepwise over 150 ft intervals. During the first 150 ft travel the yaw falls to below 5° and equation 7 is subsequently valid.

6. HOLLOW BASE FLECHETTES

6.1 Yaw, point-first

Three of these flechettes were fired point-first but two were very wild and gave no shadowgraph records. The third, although off line, flew sufficiently straight for the yaw to be recorded by nine stations over a distance of 135 ft. The yaw-travel curve for this round is shown in figure 9. The facts that the yaw for this round built up to about 20° and that the other two rounds veered well off line indicate that the stability of this hollow base flechette is insufficient to sustain it in 'arrow flight'.

6.2 Retardation, point-first

The analysis of the space-time data of the one recorded round (No. 64) gave a value for the drag constant 'a' = 0.00128. The mean yaw over the recorded distance was 19° for which angle the flechette projected area was 0.122 in². From this, C_D = 0.350 at the mean velocity 3145 ft/s (Mach 2.8), showing that C_D is lower for this finless projectile, cf. finned and flared of figure 5. The velocity-travel curve is given in figure 10 and is repeated in figure 12 for comparison with other flechettes.

For this round V_{150}/V_0 = 0.812, which, when compared with the mean value for the finned flechettes of 0.897, shows that the hollow base flechette lost velocity at about twice the average rate of the finned flechettes due to its smaller mass and greater yaw.

6.3 Yaw, backwards-launched

Six hollow base flechettes were launched backwards at three different velocity levels. Yaw-travel curves show that the flechettes turn over quickly from base-first flight, followed by a large oscillatory yawing motion which is decaying rather slowly. Figure 9 shows the yaw-travel for a typical round (Rd No. 41, M.V. 3250 ft/s). The other five rounds gave very similar yaw-travel curves, each showing that the amplitude of yaw oscillation is still of the order of 50° to 60° after 150 ft travel from the base-first launching point.

The yaw-orientation of yaw curves on polar plot shows that the yaw is planar. The angle of the plane containing the yaw varies in a random manner from round to round.

6.4 Retardation, backwards-launched

The velocity-travel curves for these flechettes launched backwards, are given in figure 10. It will be noticed that these curves do not flatten off beyond 100 ft travel as in the case of the finned flechettes - see figure 8. The yaw of the finned flechette by this distance has dropped to less than 10°, with a consequent reduction in projected area and air drag, whereas the yaw of the hollow base flechette is still over 50° (peak) at 150 ft travel.

The muzzle velocity has again been estimated from previous firing experience but may be even more inaccurate than with the finned flechette due to differences in overall projectile weight. The hollow base flechette with its sabot and base-plug weighed about 350 grain compared with 440 grain for most other projectiles fired through this gun.

From estimates of the velocities at 100 ft and 150 ft travel taken from the velocity-travel curves, the fractional velocities V_{100}/V_0 and V_{150}/V_0 were calculated for each round. The mean fractional velocities for all rounds are 0.444 (σ = 0.040) and 0.355 (σ = 0.039) at 100 ft and 150 ft respectively. The comparable values for the backwards-launched finned flechettes are 0.502 and 0.473, showing clearly that the hollow base flechette slows down much more rapidly, partly due to its lighter mass and partly to its larger average yaw which is maintained for a much greater travel range.

7. FLARED BASE FLECHETTES

7.1 Yaw, point-first

The yaw-travel curves, not reproduced, do not show any clear regularity enabling the yaw period to be established. The mean yaw over its recorded distance has been assessed for each round and is given in Table 3. The greatest yaw recorded at any position was 5.4° at 100 ft travel for round 5. One concludes from this that when fired initially point-first this flechette flies equally as true as the four finned flechette.

Because of the large base diameter to body diameter ratio the flechette must yaw through an angle of just over 3° before the nose and body contribute to the projected area. The variation of projected area with angle of yaw has been calculated for this flechette for yaw angles up to 24°. This covered most of the yaw amplitudes recorded. The mean area for each round obtained from a curve of projected area against travel is given in Table 3 and has been used in the calculation of C_D, see Section 4.2.

7.2 Retardation, point-first

The results deduced from the space-time data for the point-first rounds are summarised in Table 3. For each round the Table gives the muzzle velocity, fitted constant 'a' (see Section 5.2) and Standard Error of 'a', mean yaw, mean area, drag coefficient C_D, the mean velocity, V and the 'retardation' in ft/s per ft travel.

The recorded values of C_D are shown in figure 5 plotted against the mean velocity $\overline{V}$, expressed as Mach number. The results are more consistent than those of the finned flechette which is perhaps not unexpected; the base diameter contributes most to the form drag and does not vary between projectiles to the same extent as the fins of the finned variety.

The drag coefficient of the flared base flechette is generally only slightly higher than the U.K. or the U.S. finned flechettes. However, a comparison of the 'retardation' values given in Tables 3 and 1 show that the larger effective area of the flared base flechette causes it to lose velocity at up to twice the rate of the finned flechettes despite its heavier mass. This can be seen, although not so clearly, by comparing the slopes of the velocity-travel curves of the two different types in figure 12.

7.3 Yaw, base first

As had been suspected, this flechette did not turn to 'arrow' flight but remained base first following backwards launch. After a short travel during which the yaw increased the flechette settles to a low amplitude oscillatory planar yaw. The yaw-travel for four of the rounds has been plotted in figure 11 from which it can be seen that the flechette oscillates with amplitude 6 to 8° about a mean yaw of approximately 15°.

Table 4 gives the mean yaw over the recorded distance for each of the base-first rounds. Also quoted are values of mean projected area which are deduced from projected area-travel curves.

7.4 Retardation, base-first

Table 4 also summarises the other relevant data recorded for these base-first rounds. The drag coefficients are much higher than for any point-first rounds probably due to the very large form drag associated with the bluff leading surface, as fired.

Here again the comparison of the actual retardation at similar velocity levels show that this flechette, flying backwards, loses velocity at nearly five times the rate of the point-first finned flechette.

8. MODIFIED FLARED BASE FLECHETTES

8.1 Yaw, backwards-launched

In the introduction it was mentioned that these projectiles were to be launched from warheads with possibly large variations of initial yaw and velocity between individual flechettes. The flechette should turn quickly to arrow flight before impact on the target to achieve maximum effect. The flared base flechette would not meet this requirement in its existing form.

To effect the required turnover from base-first to point-first flight modifications to the base were obviously required. Two variants were in fact tried - see figure 1b. 1, hollowing out the base cone by a suitable conical counter boring; this would move the centre of mass further to the nose without significantly affecting the centre of pressure. And 2, a small asymmetric bevel on the base to give a large lift to the flared end, producing a resulting couple which would cause turnover. Various angles of bevel were tried.

8.1.1 Hollowed flared base

The yaw-travel was observed for three of these flechettes following a backwards launch. Each flipped over from base-first flight within about 30 ft travel, followed by a large amplitude oscillatory yaw, of period about 30 ft, which damped to approximately 60° amplitude after 100 ft total travel. The yaw-travel curve is similar to that shown for the hollow base flechette (Rd 41) in figure 9 but of slightly longer period.

From this it is seen that counter-boring the base has caused the required 'topple' to point-first flight but the subsequent oscillatory yaw is too slowly damped out for the flechette to be of much use.

8.1.2 Bevelled flared base

Rounds were fired with base bevels of 5°, 10°, 15°, 20° and 30°. All rounds veered wildly off line, particularly the 5° and 10° bevel types and observations of the yaw-travel were in consequence rather limited.

One round with a 5° bevel was fired and only four observations were obtained for it; these were in the travel range 30 to 48 ft when the flechette was still base-first with a yaw of 15° to 30°. It is not possible to say whether this flechette would eventually have turned over to point-first flight.

Two rounds were fired with 10° bevelled bases; one gave no records at all and the other had yaw of 40°, 18° and 55° (still base first) at 30, 35 and 48 ft from muzzle respectively. It is likely that at 48 ft it is turning towards point first flight but again one cannot be definite on this.

Two rounds were fired with 15° bevelled bases and each of these toppled over completely. One in fact had completed three 360° tumbles during its first 100 ft travel - the recorded portion. The other, after two complete tumbles (of 360°) in the first 55 ft travel, appeared then to turn to point-first flight with a large amplitude oscillatory yaw. This compares with the hollow base and the hollowed flared base flechettes except for the preliminary complete tumbles.

Rounds fired with 20° and 30° bevelled bases were tumbling throughout the distance of recorded travel. None of the yaw-travel curves have been produced. It is possible from the observations to make the deductions given above but it would be rather fictitious to draw a curve or curves through the observed points.

8.2 Retardation

As with the yaw-travel the data recorded for the velocity-travel history of these modified base projectiles was rather scanty. From the results which were obtained, typical velocity-travel curves for a hollowed flared base round and a 20° bevelled base round are shown in figure 12. These show the velocity to be falling rapidly over the whole of the travel range, in a manner similar to that of the backwards-launched hollow base flechette (Section 6.4); compare with figure 10.

The velocity-travel curve for the 15° bevelled base round which had shown signs of turning to point-first flight is also given in figure 12. This curve begins to flatten off at about 60 ft travel, further evidence that the tumbling motion has finished. The projectile area and air drag are then both reduced.

9. DISCUSSION OF RESULTS

9.1 Flechette stability

The stability of the flechette considered has only been examined experimentally to the extent that the yaw variation with travel has been measured. No attempt has been made to make a theoretical study of the flechette stability nor to measure the aerodynamic forces acting on and coefficients of the flechettes. The main interest was the more practical one of observing whether the flechettes would under different launching conditions settle down to 'arrow' or low yaw flight.

From the measurements already discussed it is evident that only the four finned flechette, of all those which have been fired, could at present be considered for use in a weapon warhead from which the flechettes would be impulsively launched with large variations in initial yaw.

The four finned flechettes can be closely stacked in the warhead alternately - head to tail. If they are launched such that they are initially all broadside on to their motion, they will turn to point-first flight within about 70 ft. This is assuming that during the actual launching individual flechettes do not receive large angular velocities, through jostling and so on, which must be damped out. If they are launched initially half of them point-first and half base-first, they will separate into two groups, one group remaining in point-first

flight and the second turning to point-first within about 70 ft. Again any initial angular velocity must be lost before point-first flight is achieved.

The hollow base flechettes are un-usable in their present form; the evidence of only one round shows that the yaw does not remain small in point-first flight. It is possible, however, that sufficiently stable flechettes of a composite construction - light alloy tail and heavy metal head - could be developed. Probably even these would only be launchable with small initial yaw angles. Their development would require more firings and other effort and mass production might present some difficulties.

The un-modified flared base flechettes are stable only if launched initially point-first when they will maintain a low yaw attitude. Modifications to the flechette to induce turnover from base first launch have been successful but the stabilising action of the flechette base flare is inadequate in damping out the subsequent oscillatory yaw in an acceptably small travel.

9.2 Flechette air drag

The rate at which the flechette lose velocity varies with flechette type and initial attitude on launch.

The finned flechette fired point-first loses velocity at the rate of about 10% for each 150 ft travel.

The hollow base and flared base flechettes fired point-first each lose nearly 20% of their initial velocity over this same travel, 150 ft.

Flechttes fired base first lose velocity much more rapidly. Both the 'counterbored' flared base flechette and the finned flechette lose approximately half their initial velocity in the first 100 ft travel; and other types slow down even more rapidly.

Figure 12 gives a comparison of the velocity-travel of the different types, both point-first and backwards-launched. To have included all varieties, conditions and velocity levels would have produced too confusing a graph. However, reference to figures 8 and 10 drawn to the same scales should give a complete picture.

9.3 General

The flared base flechettes appeared in the early firings to be less suitable for the warhead project than the finned base flechettes, from velocity loss and stability considerations. However, it is possible that the flechettes will be explosively launched from the warhead and the flechettes will have to withstand the explosive forces and high temperatures imposed on them. The flared base flechette will probably be able to withstand these much better than any of the other types. The finned flechette would lose all its advantages in the event of loss of or distortion of its fins. The firings with the flared base flechette were continued, in case it should prove to be the only acceptable one from this consideration alone.

10. CONCLUSIONS

The finned flechette has been shown to be sufficiently stable to turn to 'arrow' flight (less than 5° yaw) within 150 ft from a backwards-launched attitude. In the transition period, its velocity falls by about half.

An empirical equation is established which enables the velocity of a point-first finned flechette to be estimated after any given travel; this equation is used iteratively over steps of about 150 ft. The velocity falls about 10% for each 150 ft travel.

The hollow base flechette is not sufficiently stable to maintain point-first flight with a low yaw even when initially launched point-first. Flechettes of composite construction - heavy metal nose and light alloy tail - could probably be developed, requiring more firing effort.

The flared base flechette is stable enough to maintain point-first flight. Base modifications have induced turnover from a backwards launch to point-first flight; the base flare, however, does not give enough stability to damp out the ensuing oscillatory yaw rapidly enough. Possibly the use of composite construction could be used to advantage, i.e. a light alloy tail, heavy nose flechette with its hollow base flared outwards, possibly in the form of four pointed pseudo-fins to assist in stacking.

11. REFERENCES

1. Andrews, T.O. Green, K.E.B. — The B2 Aeroballistic Range. R.A.R.D.E. Memorandum in preparation

2. Piddington, M.J. — The drag characteristics of a 10.2 grain flechette, B.R.L. Memorandum Report No.1501.

Table 1

Finned flechettes, point-first

Rd No.	Charge weight grain	10^3a	10^3S.E. of 'a'	V_o ft/s	V_{150}/V_o	Mean Yaw	Mean Area sq.in.	C_D	$\overline{V}$ ft/s	'retardation' ft/s per ft
63	150	.773	.011	2026	.8906	2.0°	.0506	.650	1912	1.45
61	200	.711	.015	2532	.8989	2.1	.0520	.582	2400	1.71
60	"	.929	.016	2588	.8700	2.0	.0488	.810	2413	2.24
52	250	.693	.012	2737	.9013	2.9	.0572	.516	2598	1.80
55	"	.793	.016	2918	.8879	3.4	.0603	.560	2750	2.18
54	"	.744	.015	3008	.8944	1.8	.0461	.687	2845	2.12
53	350	.665	.017	3548	.9051	3.0	.0576	.491	3376	2.24
57	"	.659	.020	3740	.9059	2.3	.0511	.549	3560	2.35
56	"	.664	.023	3749	.9052	4.7	.0719	.393	3567	2.37
59	500	.675	.030	4750	.9037	5.0	.0745	.386	4516	3.05
58	"	.620	.014	4799	.9112	7.5	.0849	.311	4581	2.84

Table 2

Finned flechettes, backwards-launched

Rd No.	Charge weight grain	M.V. ft/s	V_o ft/s	V_{100}/V_o	Mean Yaw 100-140 ft	V_{150} ft/s	V_{150}/V_o
70	150	2210	1055	.4775	10.6°	995	.4500
68	200	2620	1415	.5400	5.4	1340	.5115
50	250	3020	1550	.5130	7.1	1465	.4850
51	"	"	1545	.5115	6.6	1465	.4850
46	350	3830	1965	.5130	6.8	1865	.4870
47	"	"	1740	.4545	8.7	1695	.4425
69	"	"	1795	.4685	6.9	1690	.4415
48	500	4865	2520	.5180	-	2425	.4985
49	"	"	2575	.5295	10.1	2400	.4930

Table 3

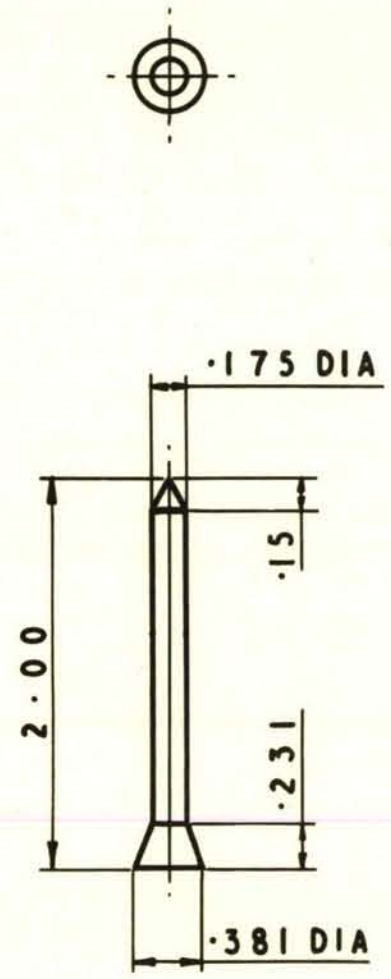
Flared base flechettes, point-first

Rd No.	Charge weight grain	M.V. ft/s	$10^3 a$	10^3 S.E. of 'a'	Mean Yaw	Mean area sq.in.	C_D	$\overline{V}$ ft/s	'retardation' ft/s per ft
17	250	2895	1.255	.017	1.0°	.1128	.653	2587	3.25
6	"	3025	1.285	.019	2.3	.1142	.661	2708	3.50
5	"	3045	1.271	.013	2.6	.1161	.643	2681	3.40
16	"	3095	1.225	.101	3.2	.1196	.602	2795	3.40
9	350	3835	1.047	.013	1.8	.1128	.545	3431	3.60
7	"	3880	1.032	.011	1.0	.1128	.537	3461	3.55
10	"	3890	1.054	.016	1.0	.1128	.549	3479	3.65
8	"	3895	1.020	.013	3.1	.1191	.503	3518	3.60
19	500	4820	0.852	.013	2.8	.1151	.435	4414	3.75
21	"	4825	0.854	.001	3.1	.1160	.433	4401	3.75
22	"	4835	0.874	.019	2.2	.1132	.454	4376	3.85

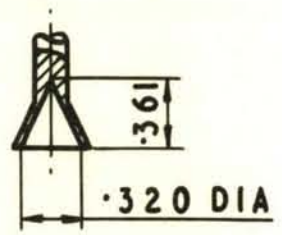
Table 4

Flared base flechette, base-first

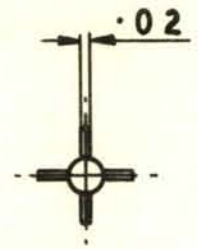
23	250	2870	3.516	.020	16°	.194	1.060	1890	6.65
25	"	2975	3.364	.020	15	.180	1.098	2005	6.75
28	350	3745	3.422	.028	13	.177	1.136	2430	8.30
26	"	3750	3.416	.030	16	.194	1.035	2540	8.70
33	500	4845	3.372	.040	15	.181	1.089	3440	11.60

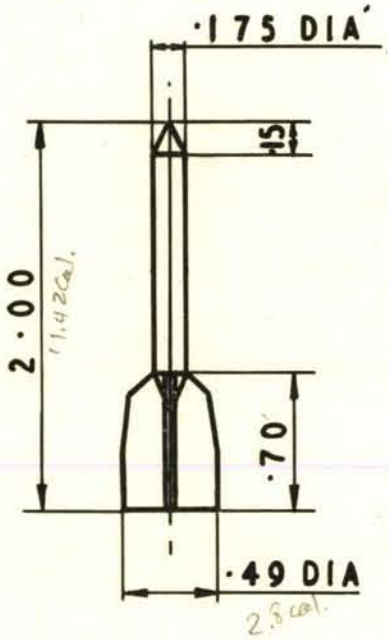


FLARED BASE
FIG. 1a

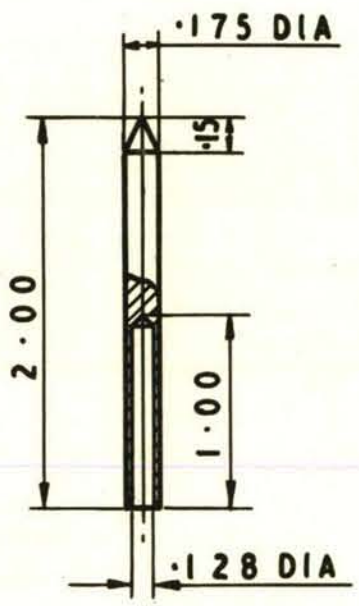


FLARED (MODIFIED)
FIG. 1b

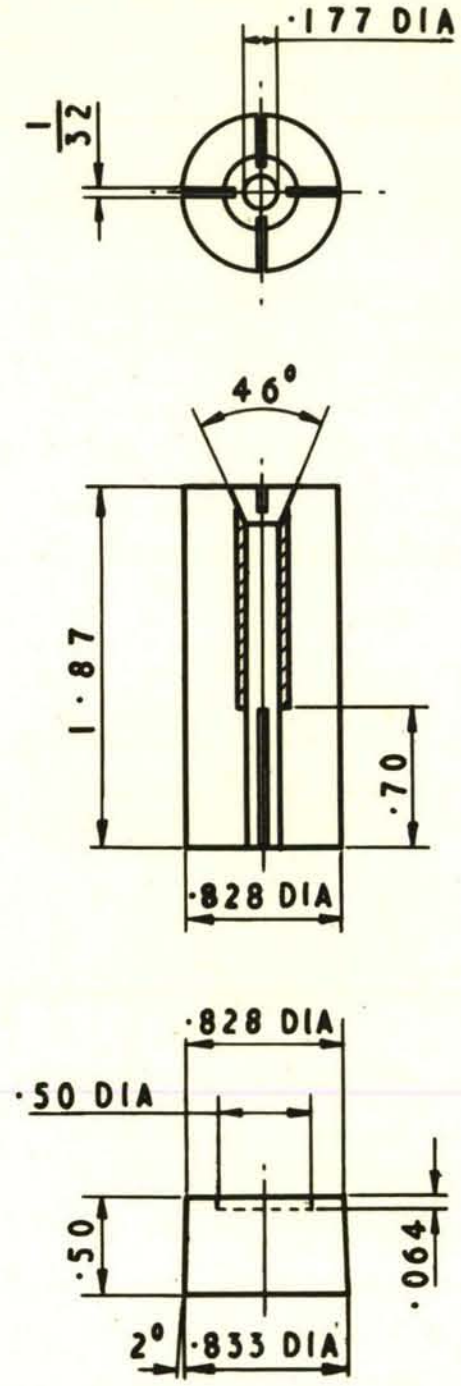




FINNED
FIG. 2



HOLLOW BASE
FIG. 3



SABOT AND BASE PLUG
FIG. 4

DIMENSIONS IN INCHES

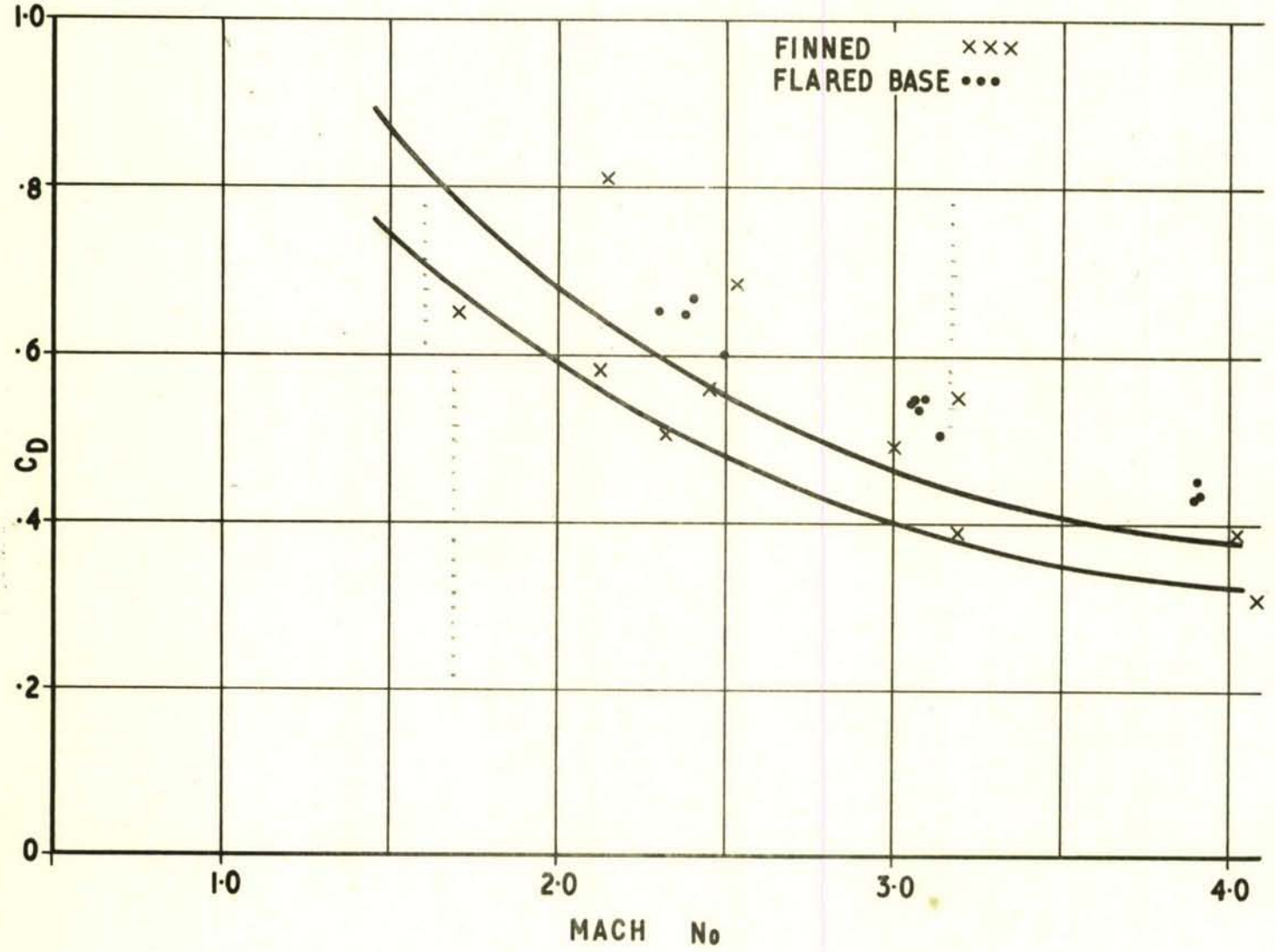


FIG. 5 FINNED AND FLARED BASE FLECHETTES (POINT FIRST)

FIG. 6

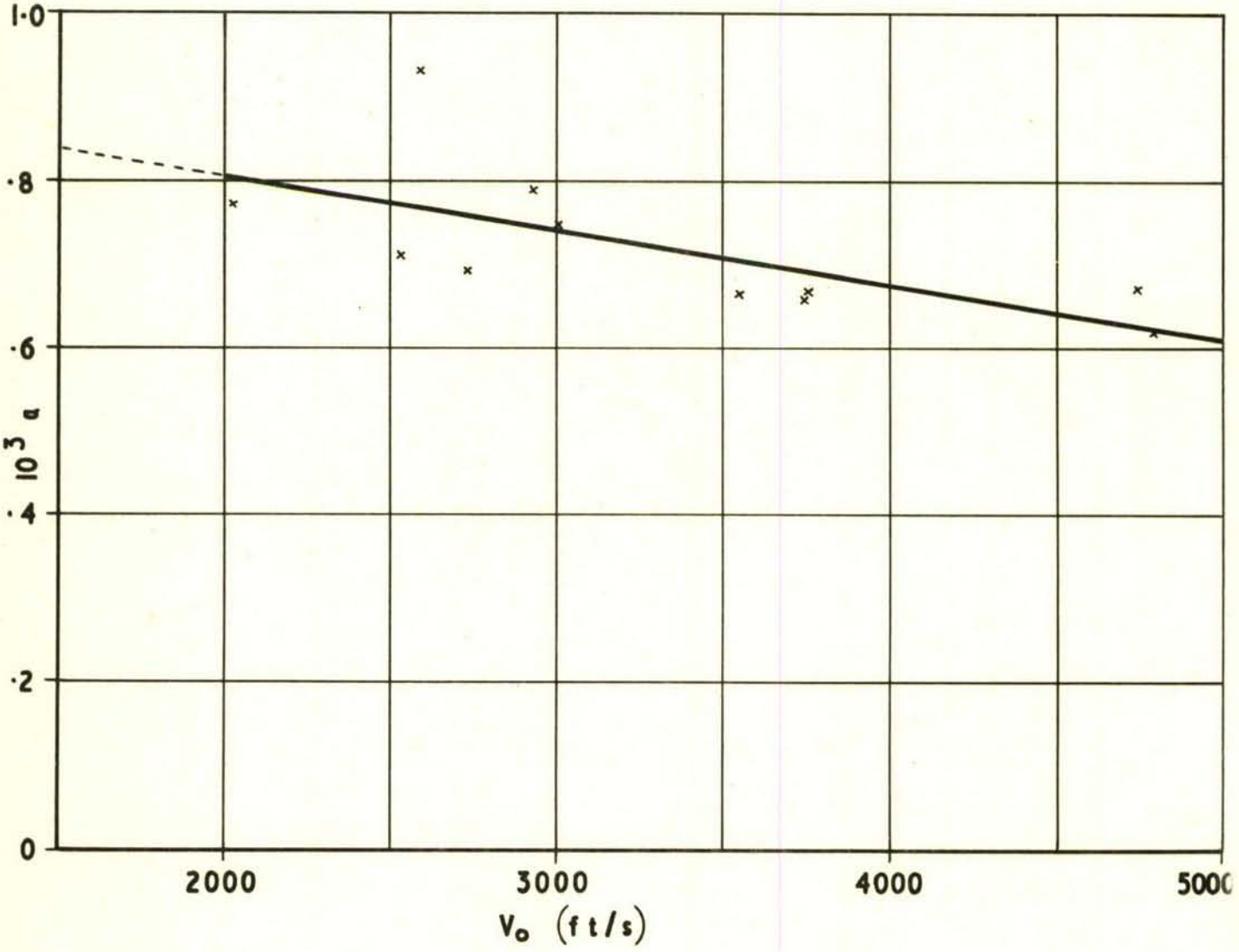


FIG. 6 FINNED FLECHETTES (POINT FIRST)

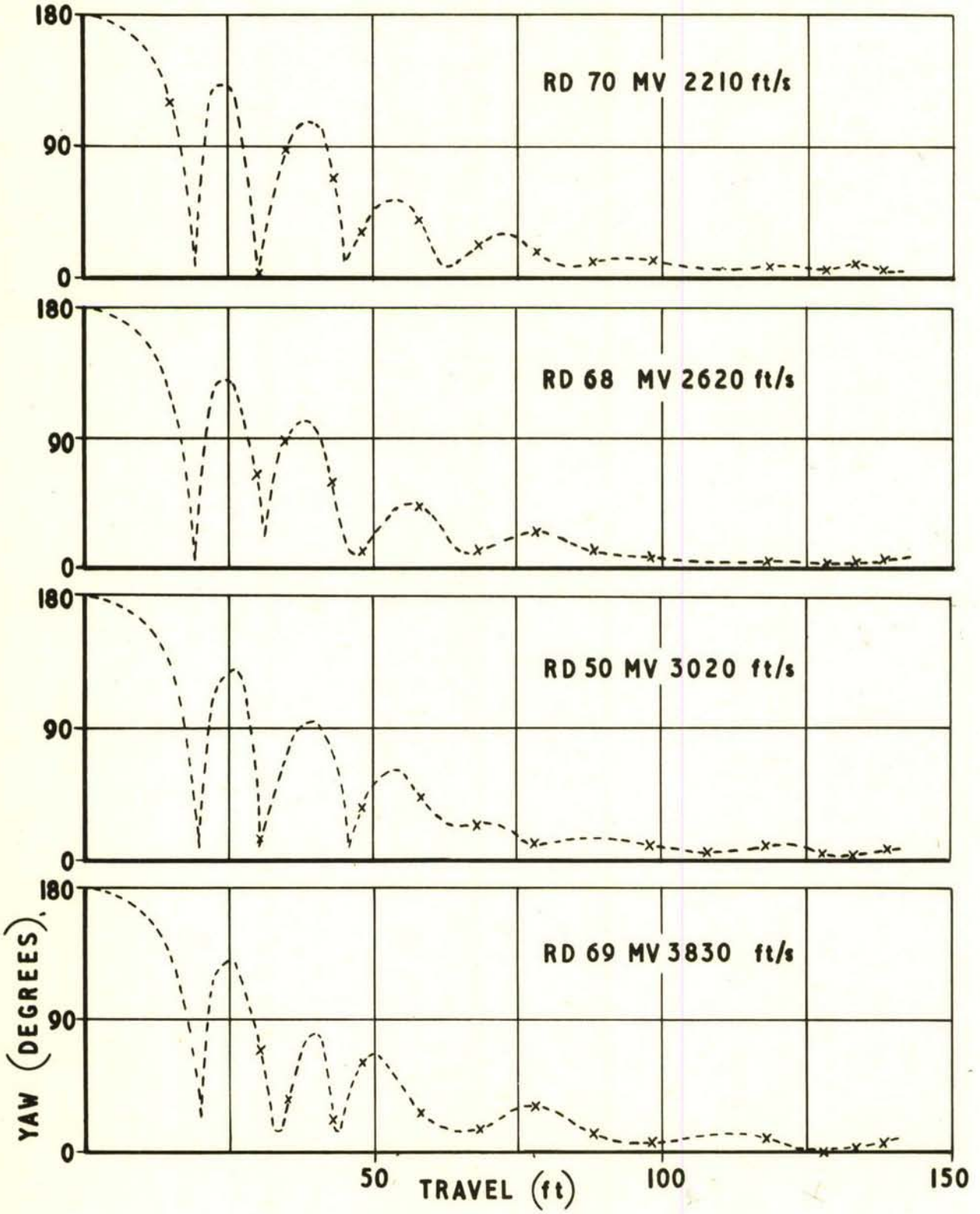


FIG. 7 FINNED FLECHETTES (BACKWARDS LAUNCHED)

FIG. 8

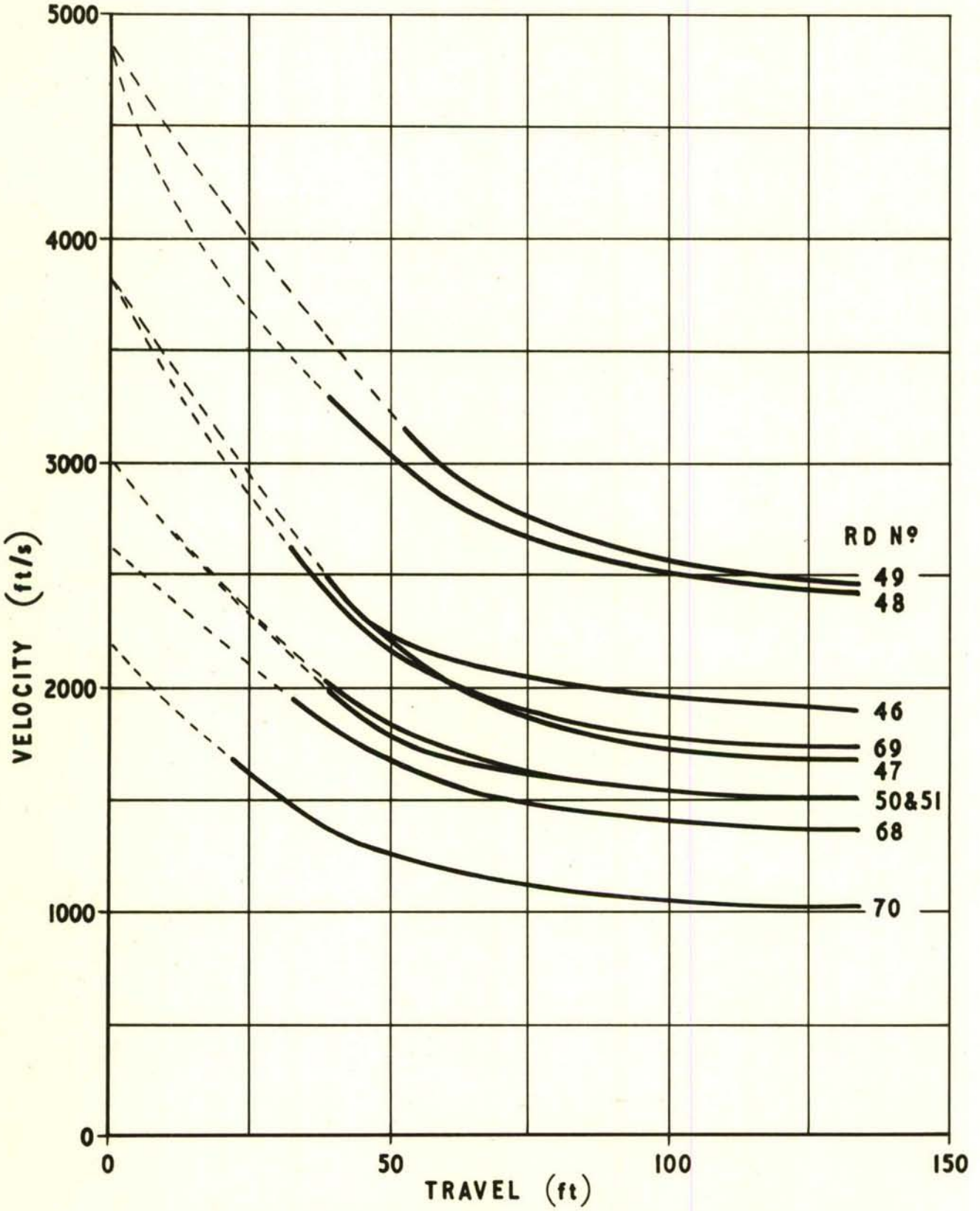


FIG. 8 FINNED FLECHETTES (BACKWARDS LAUNCHED)

FIG. 9

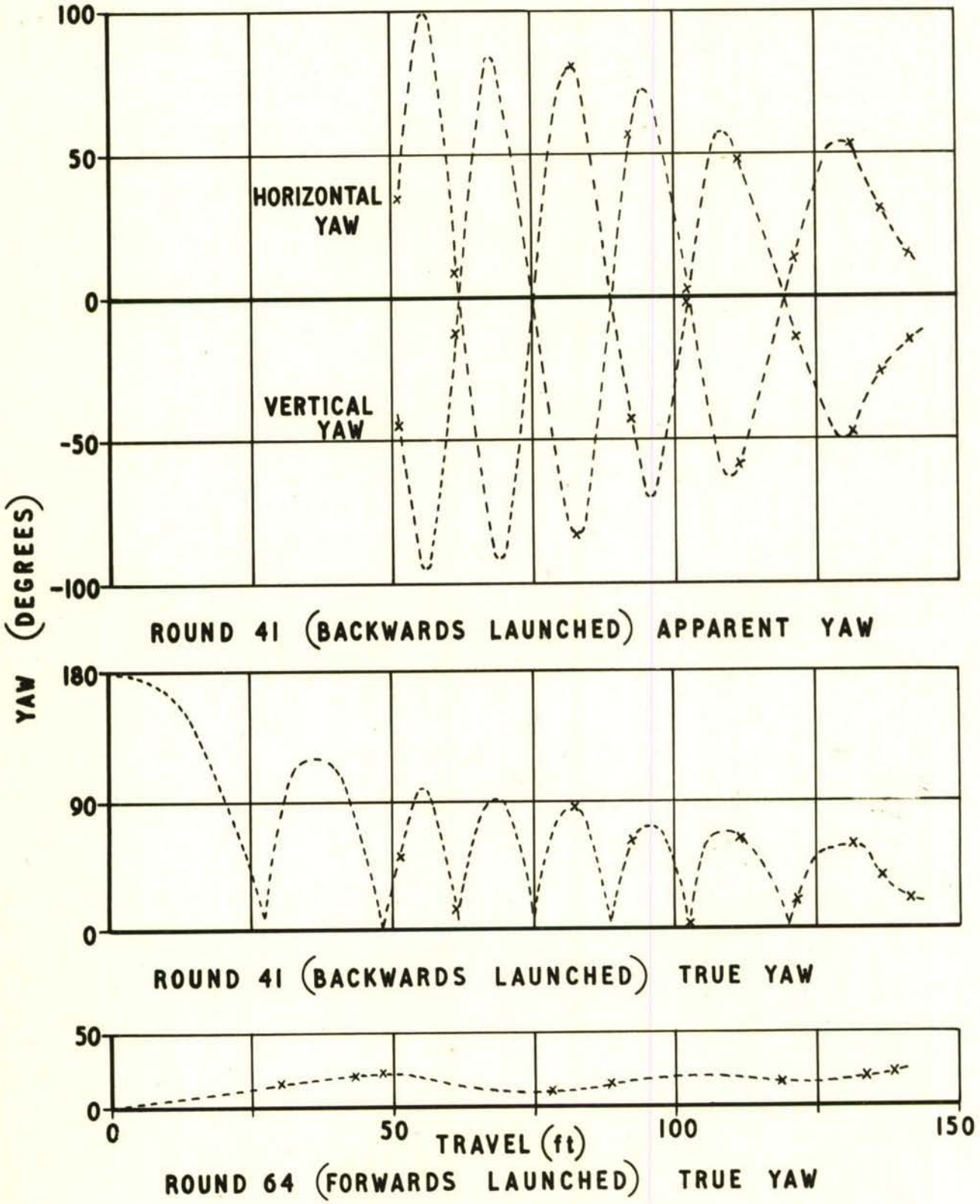


FIG. 9 HOLLOW BASE FLECHETTES

FIG. 10

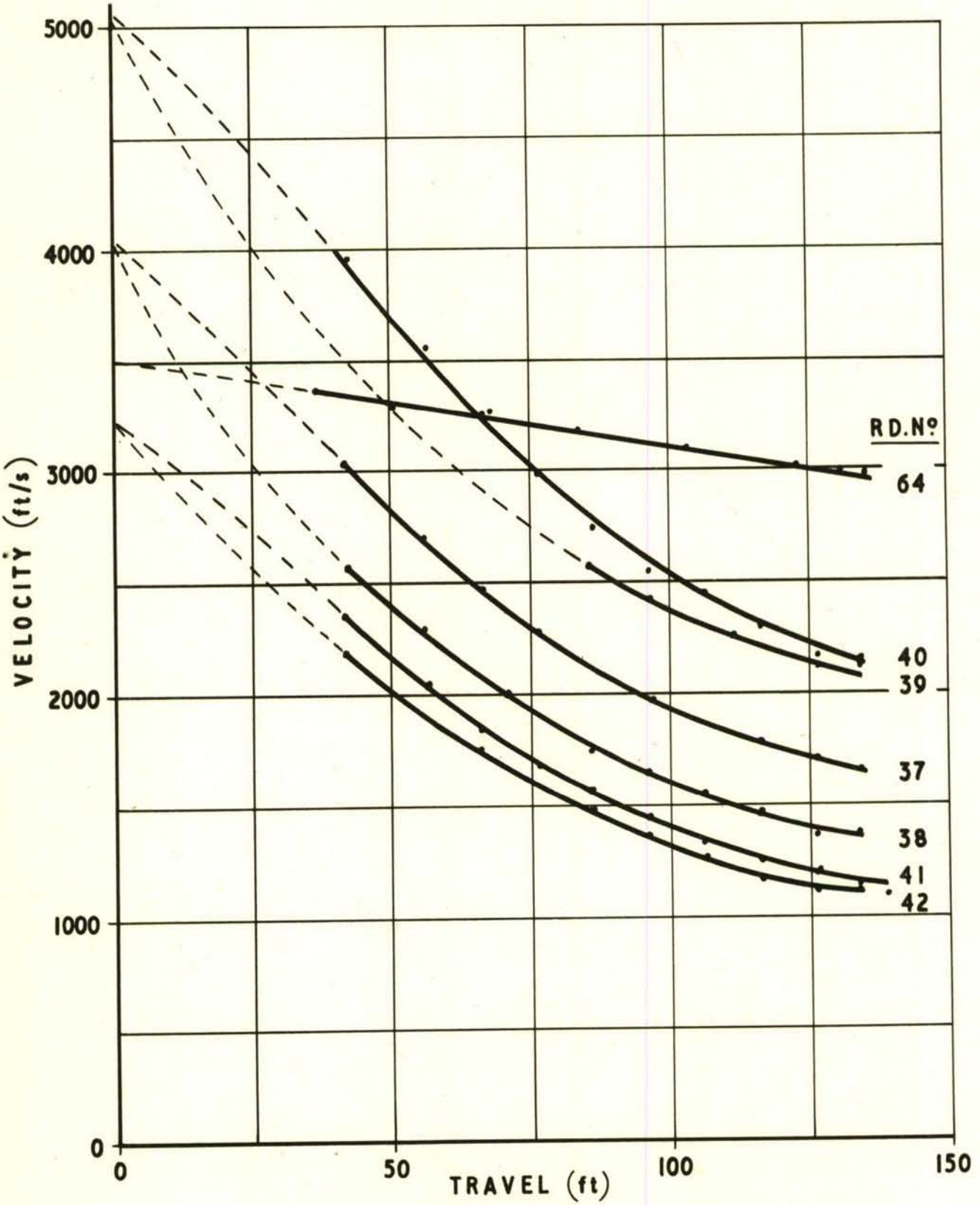


FIG. 10 HOLLOW BASE FLECHETTES

FIG.11

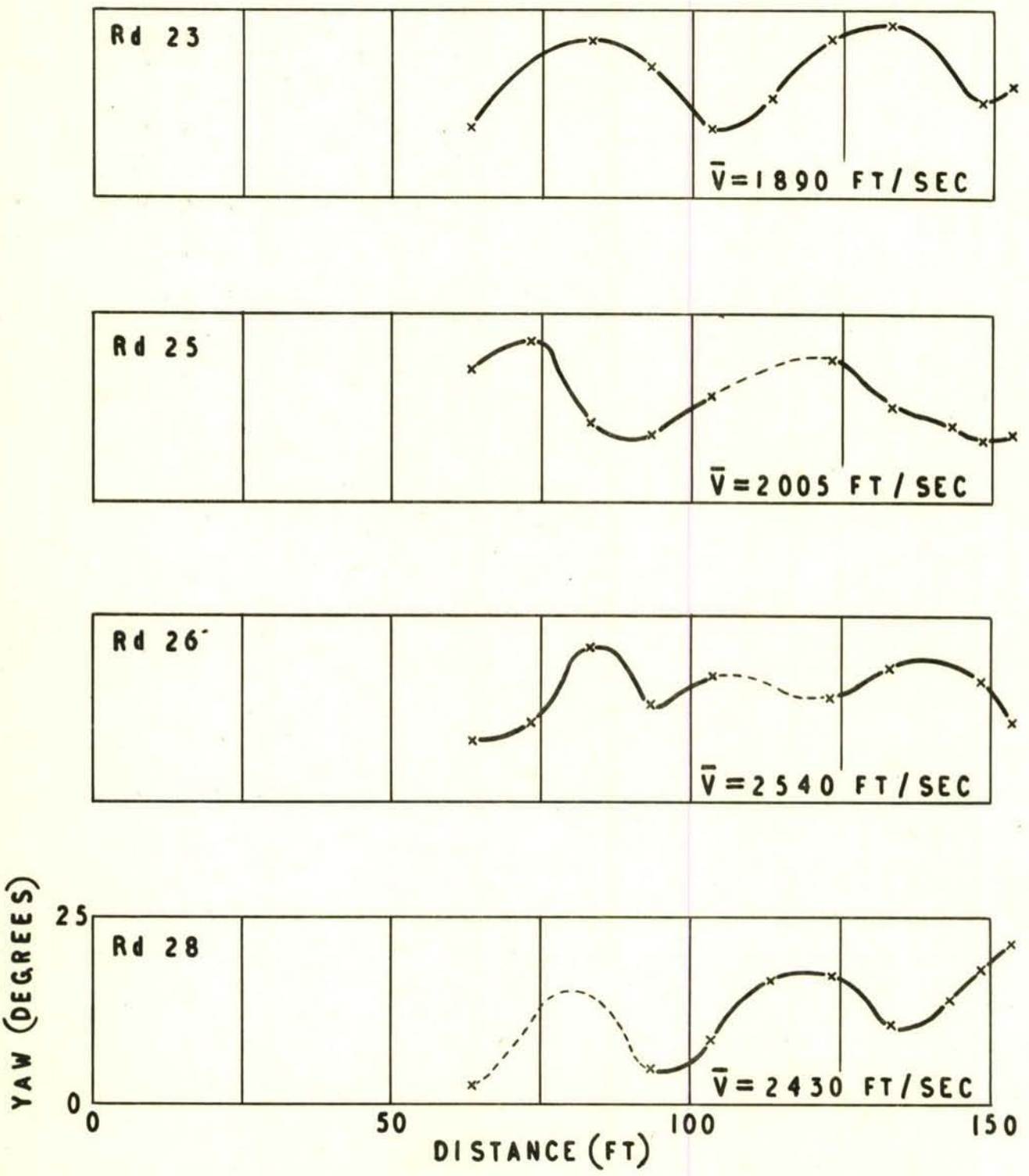


FIG.11 YAW—DISTANCE (BASE FIRST)

FIG. 12

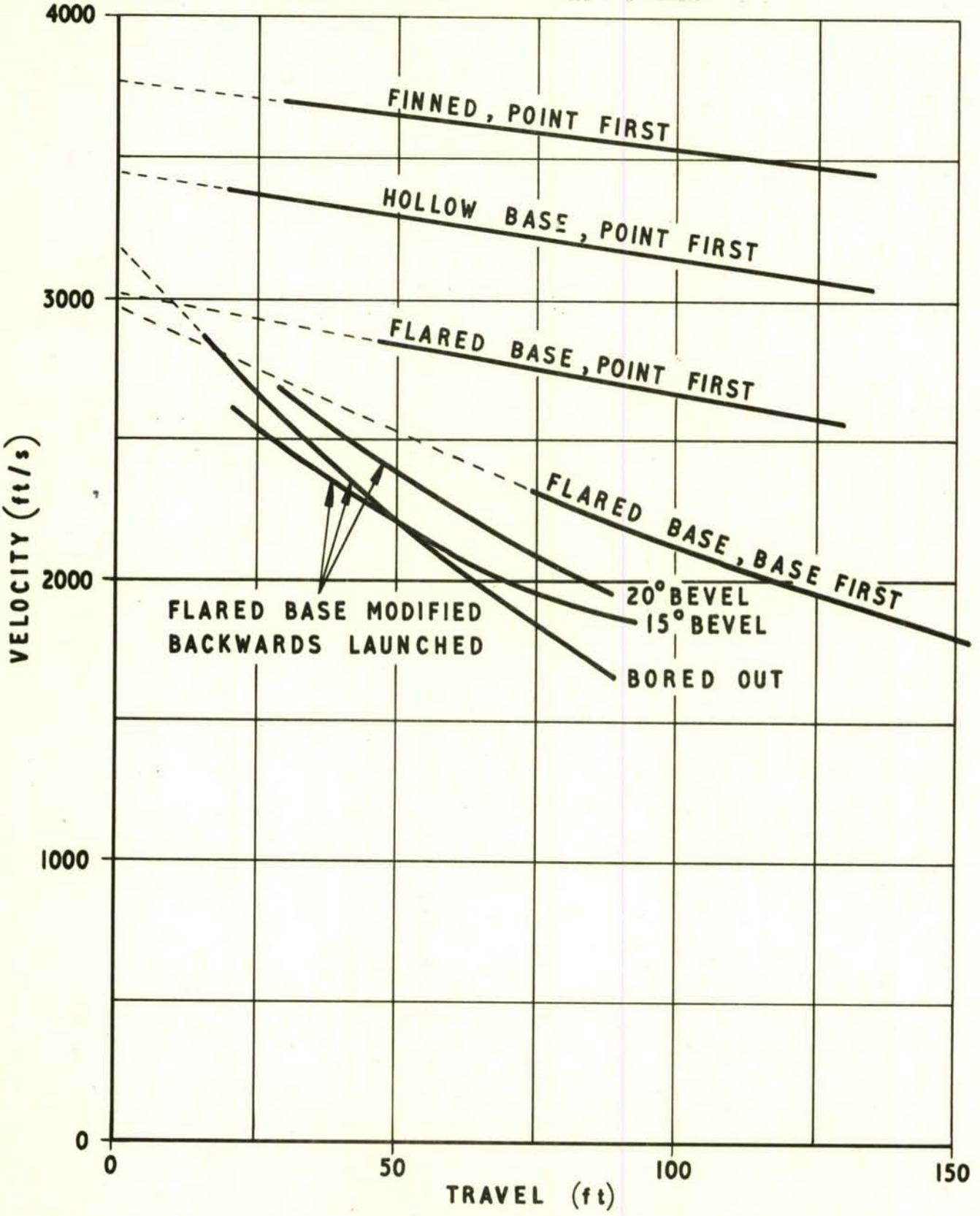


FIG. 12 VELOCITY - TRAVEL

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623.451-491:
533.6.013.12:
533.6.013.154

Measurements of the drag and yaw of '100 grain' flechettes.

K.E.B.Green. T.O. Andrews. September, 1965.

Firings in the B2 Aeroballistic Range of various designs of flechettes of $l/d = 11.4$ and order 100 grain mass have established the yaw-travel relationships for both point-first and backwards-launched rounds. The loss of velocity with travel has been measured and drag coefficients estimated where appropriate.

15pp. 12 figs. 4 tabs. 2 refs.

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